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17th June, 1955

A refrigerated disc icing meter

by

G. J. Day
(Meteorological Office)

METEOROLOGICAL
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1. Summary

The performance required from an instrument to measure rates of icing and water contents of cloud is considered and it is shown that the refrigerated rotating disc type meets most of the requirements. The design of this instrument is considered theoretically and constructional details of the model used in the Meteorological Research Flight are given. Results of wind tunnel and aircraft tests are presented.

2. Introduction

A knowledge of the supercooled water content of clouds is of importance both in the study of rainfall mechanisms and in the design of aircraft de-icing systems. In the past it has been customary to obtain values of this parameter by consideration of the rate of accretion of ice on slowly rotating cylinders or discs, of known dimensions and rate of rotation, in an air stream of known speed. Originally the weight or the thickness of ice of assumed density accumulated over a known period was measured directly but this practice proved both cumbersome and inaccurate particularly for the smaller water contents when the period of exposure was necessarily of the order of minutes. The current practice is to use a thin rotating disc continuously exposed and to measure continuously by an electrical method the thickness of ice accumulated on the edge of the disc.

A typical rotating disc design due to the Mechanical Engineering Department, R.A.E., and in use by M.R.F., is shown in Figs. 1a and b. A steel disc A, 5cm. in diameter and 2mm. thick rotates at 2 revolutions per minute, edge on to the local airstream. The thickness of ice accumulated on the edge of the disc is measured by a transducer, C, through the medium of a feeler, B; the transducer is embodied in an alternating current bridge circuit the magnitude of whose unbalanced output is a function of the supercooled water content and of the speed of the local airstream. A scraper, D, removes the ice after measurement.

Thermodynamic analysis of the heat balance of ice accretion instruments by Ludlam (1) and more recently by Fraser, Rush and Baxter (2) has shown that there is an upper limit to the accretion of ice on to a cylinder or disc at any particular ambient temperature. This limit - commonly referred to as the "Ludlam Limit" - is set by the amount of latent heat of fusion which can be transported away from the accretion surface and given to the local airstream and to the remainder of the disc. For a disc such as that described above and operating at an ambient temperature of about $-10^{\circ}C$ in an airstream of speed 180 ft. sec.$^{-1}$ the limit is about 2.0 gm. m.$^{-3}$, i.e. adequate for the majority of icing encounters.

Several authors (3), (4), (5) and (6) have recently suggested that water contents of the order of 5.0 gm. m.$^{-3}$ may be found in regions, limited in both time and space, of vigorous convective clouds of temperate latitudes, higher

/values

values being probable in tropical latitudes. It, therefore, becomes important to raise the limit of ice accretion instruments in order that they may be operated in these conditions.

3. Theoretical considerations

Adopting the symbols listed in the Appendix and applying the method of Fraser, Rush and Baxter (2) to the determination of the disc temperature appropriate to a Ludlam Limit of 6.0 gm. m.$^{-3}$, we may say that for a heat balance, i.e. equilibrium conditions at the disc edge,

$$q_v + q_k + q_f + q_i = q_w + q_c + q_e + q_s$$

but $q_v = \dfrac{hrV^2}{2JC_p}$

$q_k = \dfrac{WV^2}{2J}$

$q_f = L_f W$

$\theta_d = \theta_o + \dfrac{rV^2}{2JC_p}$ in the non-refrigerated case

$q_w = W(\theta_s - \theta_o)$

$q_c = h(\theta_s - \theta_o)$

$q_e = \dfrac{h\varepsilon L_v}{c_p p_o}(e_s - e_o)$

$q_s = k_i \dfrac{\theta_s - \theta_d}{y}$

$y = \dfrac{60mVE}{\pi n \rho_i}$

and, since at the Ludlam Limit

$q_i = 0$,

we may obtain

$$m = \frac{k_i(\theta_s - \theta_d)\pi n \rho_i}{60VE\left\{\frac{V^2}{2J}\left(\frac{hr}{c_p} + w\right) + L_f W - (\theta_s - \theta_o)(W + h) - \frac{h\varepsilon L_v}{c_p p_o}(e_s - e_o)\right\}}$$

and

$$\theta_s - \theta_d = \frac{60VEm\left\{\frac{V^2}{2J}\left(\frac{hr}{c_p} + w\right) + L_f w - (\theta_s - \theta_o)(W + h) - \frac{h\varepsilon L_v}{c_p p_o}(e_s - e_o)\right\}}{k_i \pi n \rho_i}$$

Hence in the case where

$k_i = 5 \times 10^{-3}$ cal. cm.$^{-1}$ sec. (deg.C)$^{-1}$

$n = 2$ revolutions min.$^{-1}$

/V

$V = 55 \times 10^2$ cm. sec.$^{-1}$

$h = \frac{k}{d_c} R_e^{0.5}$

$= 22.9 \times 10^3$ cal.sec.$^{-1}$ cm.$^{-2}$ deg.$^{-1}$

$C_p = 0.24$ cal.gm.$^{-1}$ (deg.C)$^{-1}$

$L_f = 76$ cal.gm.$^{-1}$

$d_e = 0.245$ cm.

$\rho_i = 0.92$ gm.cm.$^{-3}$

$E = 0.97$

$J = 4.18 \times 10^7$ dyne.cm.cal.$^{-1}$

$r = 0.85$

$W = 3.3 \times 10^{-2}$ gm.sec.$^{-1}$ cm.$^{-2}$

$m = 6.0 \times 10^{-6}$ gm. m.$^{-3}$

$p_o = 0.95 \times 10^6$ dyne.cm.$^{-2}$

we may say that since

$\theta_s = 0$ deg.C at the Ludlam Limit

and

$$\frac{hL_v}{p_o}(e_s - e_o) \ll 1$$

then

$\theta_d = -213^\circ C$ at $\theta_o = +10^\circ C$

$\theta_d = -174^\circ C$ at $\theta_o = 0^\circ C$

$\theta_d = -136^\circ C$ at $\theta_o = -10^\circ C$

Thus, in order that the rotating disc type of instrument shall accommodate those conditions considered probable, considerable refrigeration of the disc is necessary.

4. The new instrument

The new instrument is essentially a conventional rotating disc icing meter in which a hollow disc is refrigerated by the application of a stream of liquid nitrogen to its inner surface. Considering the instrument, shown broken down in Fig. 2a and assembled in Figs. 2b, c and d, in detail:-

(a) The hollow copper disc, A, mounted on a hollow steel driving shaft, B, is driven at 2 rev.min.$^{-1}$ by a 24 volt direct current motor through a chain drive contained within E. The shaft is carried in phosphor-bronze plain bearings in the casing, C.

/(b)

(b) Refrigeration of the disc is achieved by the flow of liquid nitrogen through the hollow driving shaft into the hollow disc via the feed pipe, F, and the liquid nitrogen trap, N; the latter is incorporated to prevent damage of neighbouring aircraft components by excess liquid nitrogen. The refrigerant is forced to the disc by pressure from an air bottle as indicated in Fig. 3, the rate of flow, and hence the degree of refrigeration, being governed by the air pressure used. Flow of the refrigerant is governed to obtain a nominated disc temperature as indicated by the spring loaded thermometer, G_1, bearing on the under-side of the disc. The thermometer is shown broken down as G_2 in Fig. 2a where 'a' is a copper core and shoe contained within an anodised aluminium former 'b' on which is wound a platinum wire resistance element, the whole being enclosed within a plastic insulating casing 'c' designed to reduce casual heat flow into the system. Although the temperature required is strictly that of the edge of the disc, it is considered that the surface temperature in the position adopted does not depart materially from that required; further, owing to the low rotational speed and the smoothness of the surfaces concerned, frictional heat input at the thermometer shoe may be neglected.

(c) Ice thickness is measured by the transducer, I, through the feeler, H, feeler tension being adjusted by the ratchet device, J, reached through the access panel, L, in the streamlined outer casing, K. The transducer is incorporated in an alternating current bridge circuit shown in Fig. 4 and the rectified output of the unbalanced bridge circuit displayed either on a micro-ammeter or a galvanometer recorder.

(d) After detection the ice accumulated is removed from the disc edge and adjacent top and bottom surfaces by the scraper system, M. Ice forming on the streamlined housing of the instrument is removed by the flow of de-icing fluid through a thick strip of felt, O, covered with fine copper gauze incorporated in the leading edge of the housing. A certain amount of fluid reaches the top decking of the instrument beneath the disc and assists in clearing the ice removed by the scraper. Of this fluid a small amount reaches the disc edge but since the de-icing properties result only on application to an ice-metal interface there is no effect on the amount of ice measured. Any fluid which reaches the edge of the disc does so only after the removal of the ice by the scraper system. This fluid is removed by the airstream before this part of the edge of the disc travels to the position where it again starts to collect ice. Fluid is forced to flow in an analogous manner to that used in the case of the refrigerant and the details are shown in Fig. 3.

5. Laboratory tests of the instrument

These were performed in the Icing Wind Tunnel of R.A.E. by courtesy of Mechanical Engineering Department, and were directed towards:-

(a) Ensuring that the instrument was reliable during protracted periods of operation under full refrigeration.

(b) Ensuring that de-icing fluid at normal rates of supply did not affect accretion of ice on to the disc edge.

(c) Verifying the efficient operation of the cutter system.

(d) Examining the theoretical calibration of the instrument under a variety of typical conditions.

(e) Determining the value of ρ_l under typical conditions.
Considering these tests - which were made with the rig shown in Fig. 5 - in turn:-

/(a)

(a) It proved very difficult to avoid bearing seizure under maximum refrigeration and it was necessary to use rather generous clearances and to provide forced lubrication of the bearings with de-icing fluid. As originally designed the instrument was fitted with a plain copper disc but it was apparent both from theoretical considerations and from experiment that there was serious heat input into the system from the local airstream through the disc surface. Whilst it was not possible to overcome this defect during tunnel tests it was afterwards found possible to coat the disc, save the accretion surface, with a sheath of polythene about 2 mm. thick. This modification permitted a considerable reduction in the flow of liquid nitrogen for the more extreme conditions and made the bearing operating conditions much more favourable, thereby greatly improving reliability.

An early difficulty arose in the use of light alloy gearwheels in transmission of the motor drive to the main shaft. The gearwheels used were of comparatively shallow tooth depth and under full refrigeration contracted out of mesh. It was finally found necessary to abandon the original gear box and to resort to chain drive which proved quite reliable.

(b) Tests were made under a variety of representative conditions and no difference was detected in the output of the instrument under steady conditions when de-icing fluid was switched on or off.

(c) The cutter system was found to be extremely efficient although it was found that it flaked off all ice up to a point about 10° ahead of the cutter; it was therefore necessary to reposition the feeler to avoid disturbance of the feeler system.

(d) The Icing Wind Tunnel at R.A.E. was designed to produce water contents of the order of 4.0 gm.m.$^{-3}$ at speeds of about 100 mi.hr.$^{-1}$ and at temperatures ranging from ambient to about -30°C. It was therefore not possible to check the theoretical calibration over the full range of anticipated conditions nor was it possible to establish the calibration of the instrument accurately over the available range since the calibration of the tunnel itself is not known with sufficient accuracy. Further, in the absence of an insulating covering of the disc the degree of refrigeration available prevented operation of the instrument beyond these limits save at the lower air temperatures and it was necessary to use the uncovered disc in order that the surface temperature measurements should be reasonably accurate during this stage.

Within the tunnel limits, therefore, the response of the instrument to variable water content was obtained at a steady airspeed of 100 mi.hr.$^{-1}$ and at a variety of ambient conditions; in all cases observations were made under equilibrium conditions - a much more stringent condition than those of normal operation. The results of these experiments are shown in Fig. 7 and from them was deduced a provisional empirical calibration and the variation of the Ludlam Limit of the instrument with the degree of refrigeration; these are shown in Figs. 6c and 8 respectively. It will be observed that there is a wide divergence between Figs. 6c and 6b.

Considerable extrapolation in Fig. 8 shows that the desired Ludlam Limit of 6.0 gm. m.$^{-3}$ may be achieved with a disc temperature of about -100 deg. C, in reasonable agreement with the theory when the degree of extrapolation and the known inaccuracy of the empirical calibration is considered.

(e) By flotation tests using a variety of organic liquids non miscible with water the value of ρ_i for ice formed on the edge of the disc under typical operating conditions was found to be 0.92 ± 0.02 gm.cm.$^{-3}$.

6. Air tests of the instrument

These were directed principally to confirmation of the laboratory tests and to obtaining preliminary information concerning the maximum water content to be found in natural clouds. Particular attention was paid to the operation of the instrument as a water content meter in "warm" clouds.

/Traverses

Traverses were made at various ambient temperatures through both convective and layer clouds and the maximum water contents encountered are shown in Table 1. The instrument was found to operate quite satisfactorily under all the conditions encountered and has been adopted for routine work at M.R.F.

7. Accuracy of the instrument

The calibration obtained from the expression

$$y = \frac{60 m V E}{\pi n \rho_i}$$

having been shown to be seriously in error resort was made to an empirical calibration and the accuracy of the instrument calibration became directly dependent on that of the tunnel in which it was tested. The Icing Wind Tunnel at Artington has been calibrated by exploring the working section with a heated intake having unity velocity-ratio connected to a Dobson-Brewer Frost-Point Hygrometer. The distribution of water contents so obtained was integrated and normalised with reference to the input of water into the tunnel, the final distribution of water contents being accepted as the calibration of the working section.

Extreme care was taken in the calibration of the working section and the effect of all the tunnel variables on the calibration examined. The view of the tunnel operators is that this calibration is probably accurate to ± 5% and the experience of the Mechanical Engineering Department, R.A.E. supports this view.

An empirical calibration obtained in the Artington tunnel and used to obtain the figures presented in Table 1 is shown in Fig. 6d.

Discrepancies between the values obtained from the expression above and those obtained practically arise from the interpretation of E since all the other factors are accurately known. Comparison of the two calibrations suggests an empirical value for E of 0.48.

It appears that the constant E should be replaced by one E' which represents the joint effect of the true aerodynamic collection efficiency, E, and a further factor, S, which one might term the "shape factor". The collection efficiency, E, is a function of the shape and dimensions of the instrument and can only be obtained by calculations such as those of Langmuir and Blodgett (7). It does not appear, however, that any great inaccuracy arises in the adoption of the value calculated thus.

The factor, S, arises from the fact that the ice forming on the disc edge does not do so in the rectangular section implied in the equation above but in a more rounded section and further that some of the water tends to flow back from the disc edge before freezing. This factor is not one amenable to calculation and not readily obtainable experimentally.

Both factors are implicit, however, in the empirical calibration.

The question of the departure of the in flight calibration from that obtained in the wind tunnel arises. Any departure arises from variations in E and S due to variations in ρ. It is not considered that any appreciable variation occurs in S and calculations based on Reference 7 indicate that variations in E do not exceed 1% within the altitude range normally used.

The accuracy of the instrument, then, is probably better than ± 10% in the conditions normally encountered.

/8.

8. Conclusion

A reasonably reliable research tool for the measurement of liquid water contents in natural clouds, both "warm" and supercooled, has been produced. Although crude in concept it is, so far as the author is aware, the first successful attempt to measure, continuously, water contents of the order of 4.0 $gm.m^{-3}$.

The preliminary measurements made with this instrument suggest that water contents rather higher than commonly supposed are to be found within convective clouds approaching maturity and that the full theoretical water contents may well be approached. A full investigation of this contention has been commenced and will be the subject of a further report.

9. Acknowledgements

(i) Acknowledgement is particularly due to Mr. F. A. Gordon who constructed the instrument and assisted in the wind tunnel testing. Much of the detail design is due to him and without his enthusiastic and skilful co-operation it is doubtful whether the project could have been carried to a successful conclusion.

(ii) Acknowledgement is due to Mechanical Engineering Department, R.A.E. who provided the wind tunnel facilities and to Mr. F. J. Bigg of that department, with whom the design was discussed from time to time.

10. References

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APPENDIX I

q_f = heat of fusion of impinging water, cal.sec.$^{-1}$cm.$^{-2}$

q_k = kinetic heating of water droplets, cal.sec.$^{-1}$cm.$^{-2}$

q_i = heat lost as ice cools from 0 deg.C to θ_s deg.C, cal.sec.$^{-1}$cm.$^{-2}$

q_v = kinetic heating from the air, cal.sec.$^{-1}$cm.$^{-2}$

q_w = heat required to raise water temperature from θ_o deg.C to θ_s deg.C, cal.sec.$^{-1}$cm.$^{-2}$

q_c = convective heat losses, cal.sec.$^{-1}$cm.$^{-2}$

q_e = evaporative heat loss, cal.sec.$^{-1}$cm.$^{-2}$

q_s = conductive heat loss, cal.sec.$^{-1}$cm.$^{-2}$

θ_o = ambient air temperature, degrees centigrade

θ_s = icing surface temperature, degrees centigrade

θ_d = disc temperature, degrees centigrade

L_f = latent heat of fusion, cal.gm.$^{-1}$

L_v = latent heat of vaporisation, cal.gm.$^{-1}$

W = rate of water impingement, gm.sec.$^{-1}$cm.$^{-2}$

E = collection efficiency of disc

m = liquid water content of air sample, gm.cm.$^{-3}$

V = speed of local airstream, cm.sec.$^{-1}$

J = mechanical equivalent of heat, joules cal.$^{-1}$

r = recovery factor, in this case that for a cylinder whose diameter is the edge thickness of the disc

C_p = specific heat of air, cal.gm.$^{-1}$ (deg.C)$^{-1}$

h = coefficient of convective heat transfer, cal.sec.$^{-1}$cm.$^{-2}$(deg.C)$^{-1}$
$= \frac{k}{d_c} . R_e^{0.5}$

p_o = barometric pressure, dynes cm.$^{-2}$

e_s = vapour pressure of water at θ_s, dynes cm.$^{-2}$

e_o = vapour pressure of water at θ_o, dynes cm.$^{-2}$

k = thermal conductivity of air, cal.cm.$^{-1}$sec.$^{-1}$ (deg.C)$^{-1}$

k_i = thermal conductivity of ice, cal.cm.$^{-1}$sec.$^{-1}$(deg.C)$^{-1}$

ρ_i = density of ice, gm.cm.$^{-3}$

n = rate of rotation of disc, rev.min.$^{-1}$

y = thickness of ice on disc edge, cm.

d_e = thickness of edge of disc, cm.

R_e = Reynolds number for disc, using the edge thickness as the significant length

ρ = air density, gm.cm.$^{-3}$

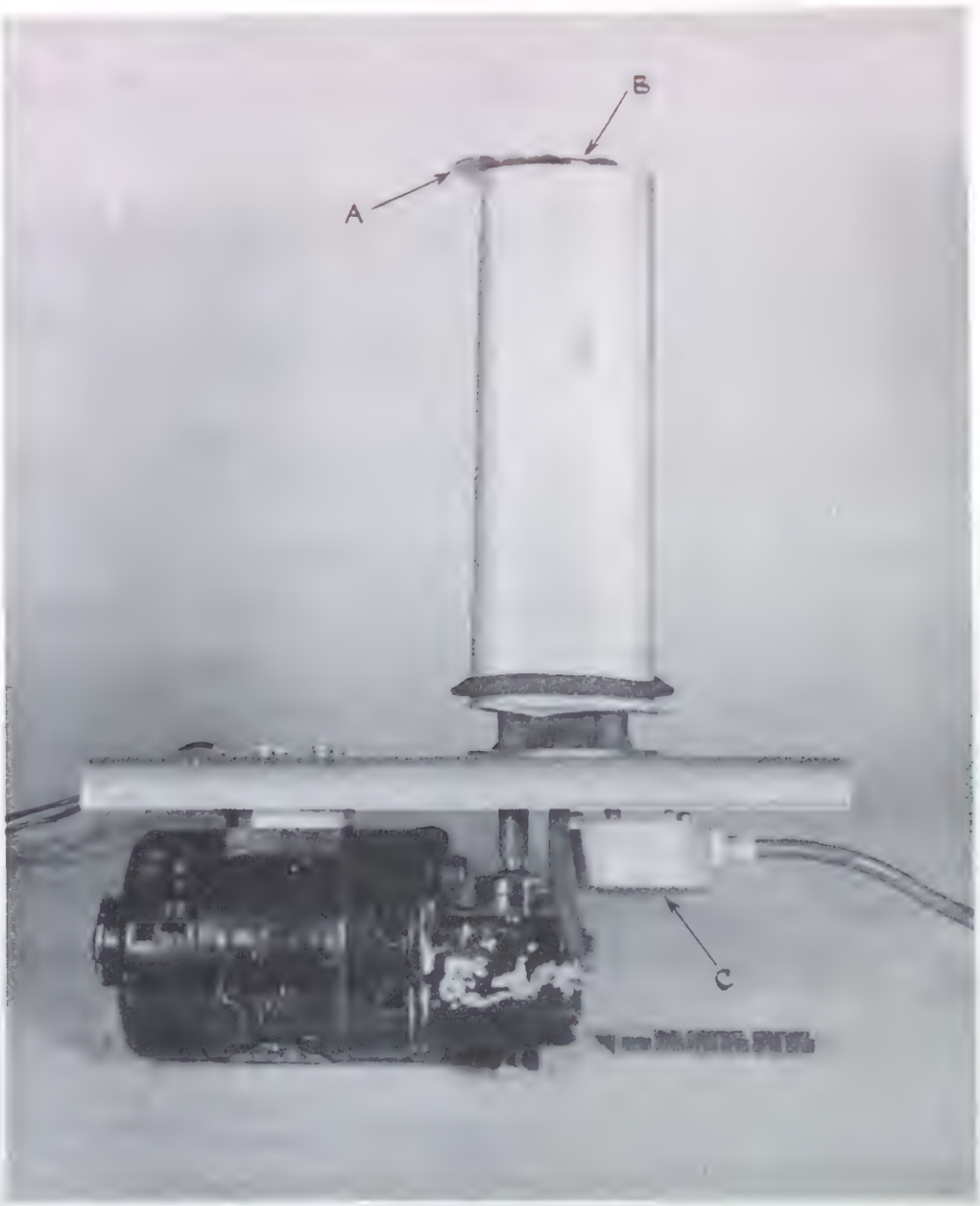
ϵ = specific gravity of water vapour = 0.622

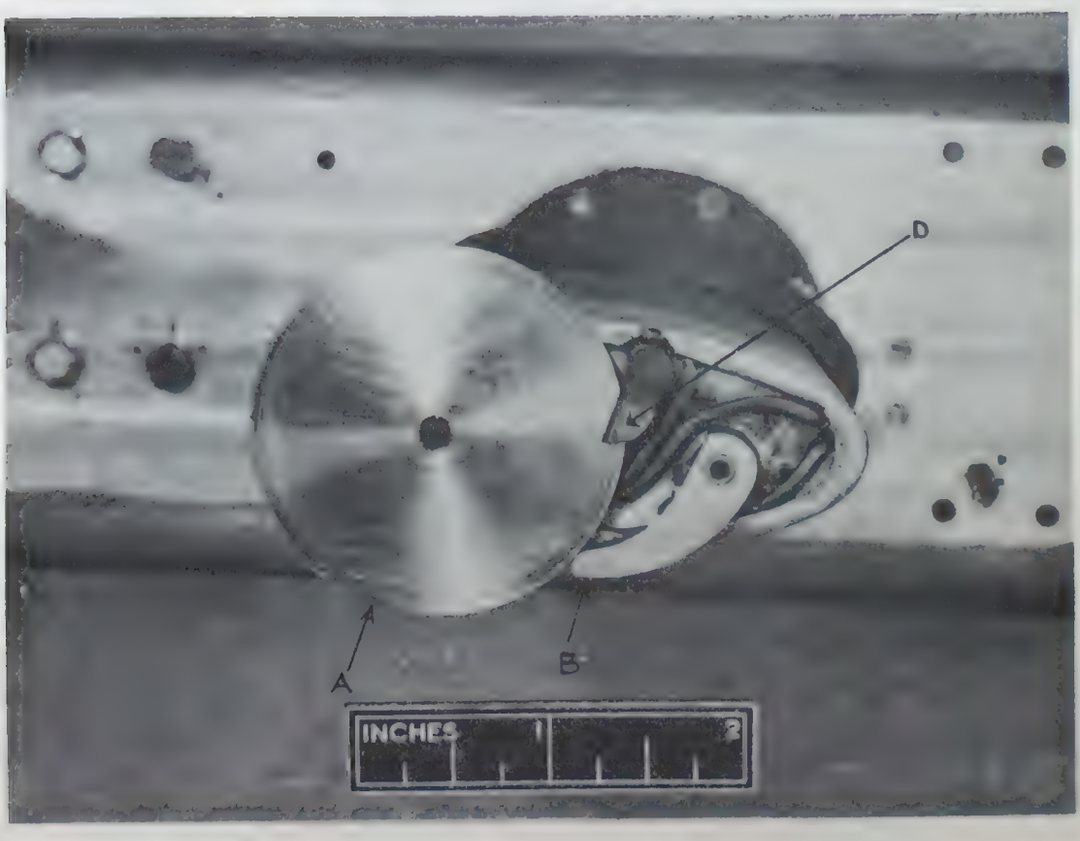
TABLE 1

Date	Time, hr. local	Place	Height ft.	Maximum water content gm.m.-3	Temperature deg. F.	Remarks
15. 6.54	15.00	Local	7000	1.18	39.8	Cumulus
27.10.54	16.30	Local	6000	a. 1.17 b. 1.14	41.0	Cumulus
28.10.54	15.00	Barra Head	3500	a. 0.54	31.0	Rain below Cumulonimbus
			4300	b. 0.25	29.5	Rain below Cumulonimbus
				c. 0.70		Base of Cumulonimbus
	15.30	Isle of Man	11500	d. 0.59	13.1	Altostratus
	16.00	North Wales	7500	e. 0.34	29.8	Stratocumulus
	16.40	Local	3700	f. 0.29	45.0	Stratocumulus
10.11.54	12.20	Boscombe Down	10000	a. 0.57 b. 1.71 c. 2.29 d. 3.55 e. 4.20	20.6	Thick deck of cold front cloud. Embedded Cumulonimbus to 30000 ft. also reported by Boscombe Down aircraft. Peak values for periods of 10 - 15 sec.
	12.40	Local	1800	f. 0.49	42.5	Stratocumulus
10.11.54	16.30	Local	8400	a. 1.30	20.7	Small cumulus
	16.45	Local	7600	b. 0.74	25.4	Small cumulus
12.11.54	15.40	Poole	6000	a. 0.28	23.0	Shallow cumulus entering decay stage
	15.45	Poole	5300	b. 0.44	23.5	
22.11.54	16.13	Swansea	5600	1.49	31.9	Frontal cloud, embedded Cumulonimbus
24.11.54	10.40	(10.m. South of	8200	a. 1.55	19.3	Cumulus over Channel approaching maturity
	10.50	(Brighton	7900	b. 1.30	19.7	
	10.55	(30 m. South	8300	c. 0.57	18.4	Cumulus just past maturity; these clouds produced showers at 11.18 when base dropped from 1600 ft. (38.5°F) to 1270 ft. (40.2°F)
	11.05	(of Brighton	8100	d. 1.98	19.4	
	11.10		7600	e. 1.09	19.1	
23.11.54	12.25	Local	6800	0.87	23.6	Cumulus, base 1900 ft.

TABLE 1 continued

Date	Time, hr. local	Place	Height ft.	Maximum water content gm.m.$^{-3}$	Temperature deg. F.	Remarks
25.11.54	11.55	Isle of Wight	6000	a. 0.48	31.2	Cumulus, base 1900 ft., 47.0°F
	11.58	" "	6020	b. 0.36	27.4	
	12.05	" "	7050	c. 1.11	27.6	Cumulus, base 1900 ft., 47.0°F
	12.15	" "	7500	d. 1.17	28.0	at maturity. Peaks last 5 - 10 sec.
30.11.54	12.25	English Channel	12000	a. 3.20	4.0	Cumulus close to maturity and about to
	12.35	" "	12800	b. 2.61	- 1.1	glaciate
	12.40	" "	10900	c. 3.75	7.9	
1. 12.54	15.40	English Channel	9000	a. 0.34	17.0	Cumulus approaching maturity, visibility
	15.45	" "	9000	b. 0.68	17.0	occasionally 5 yd.
	16.00	" "	8500	c. 0.75	19.4	





Figs. 1a. and b. Conventional Rotating Disc Icing Meter.

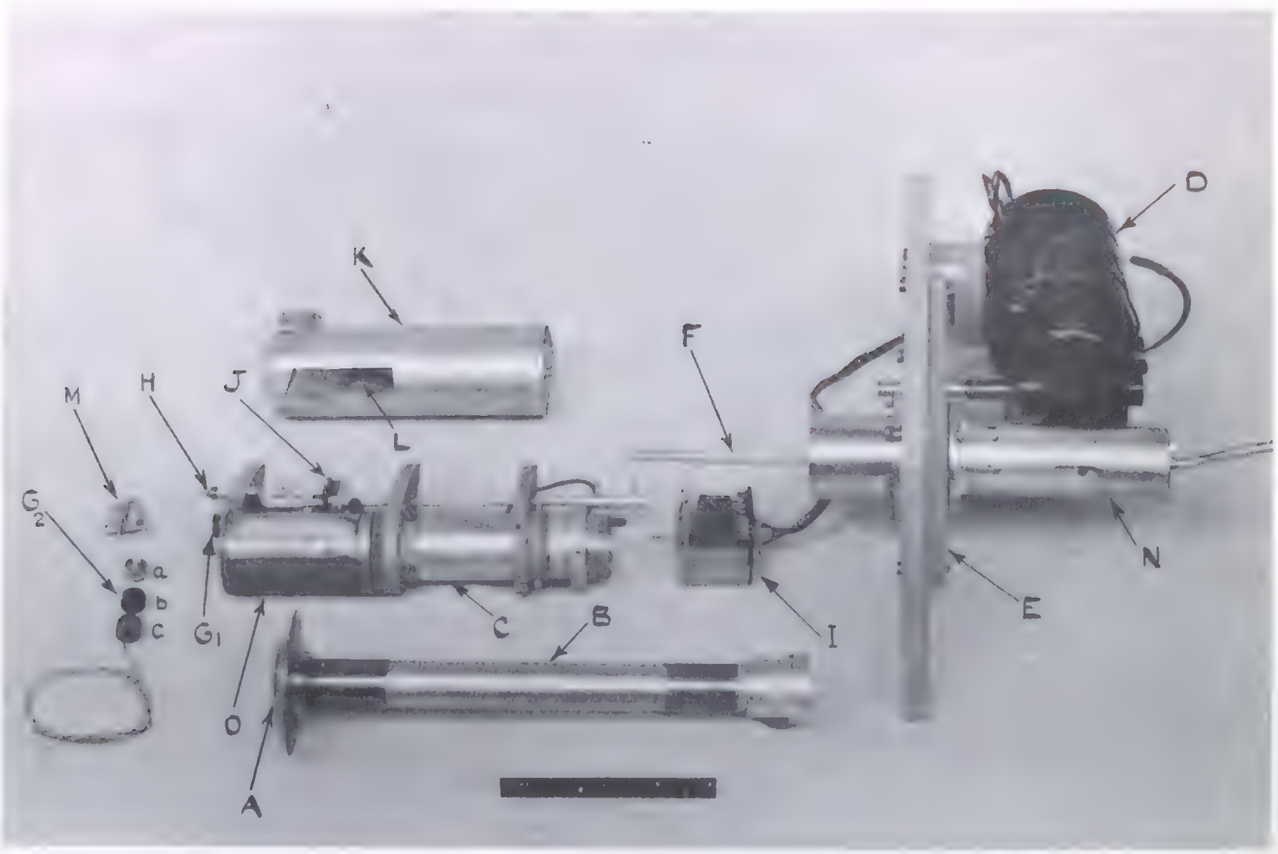


Fig. 2a. Refrigerated Rotating Disc Icing Meter Components.

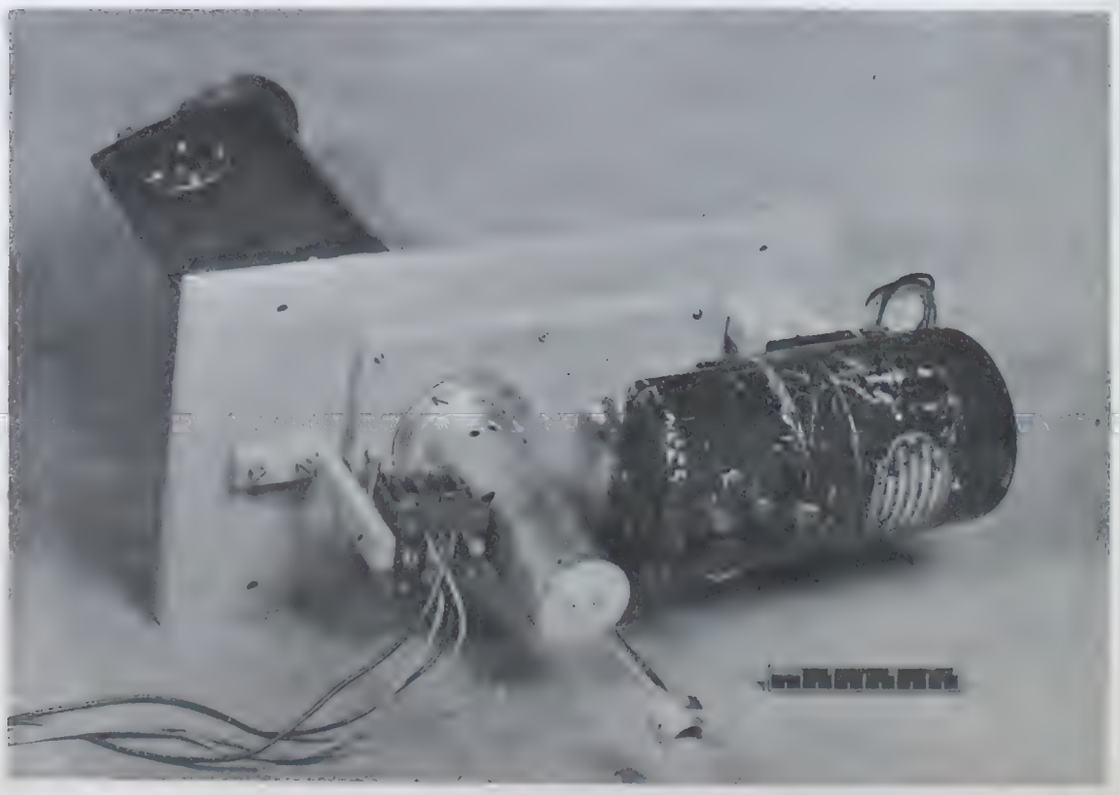


Fig. 2b. Refrigerated Rotating Disc Icing Meter - Bottom View

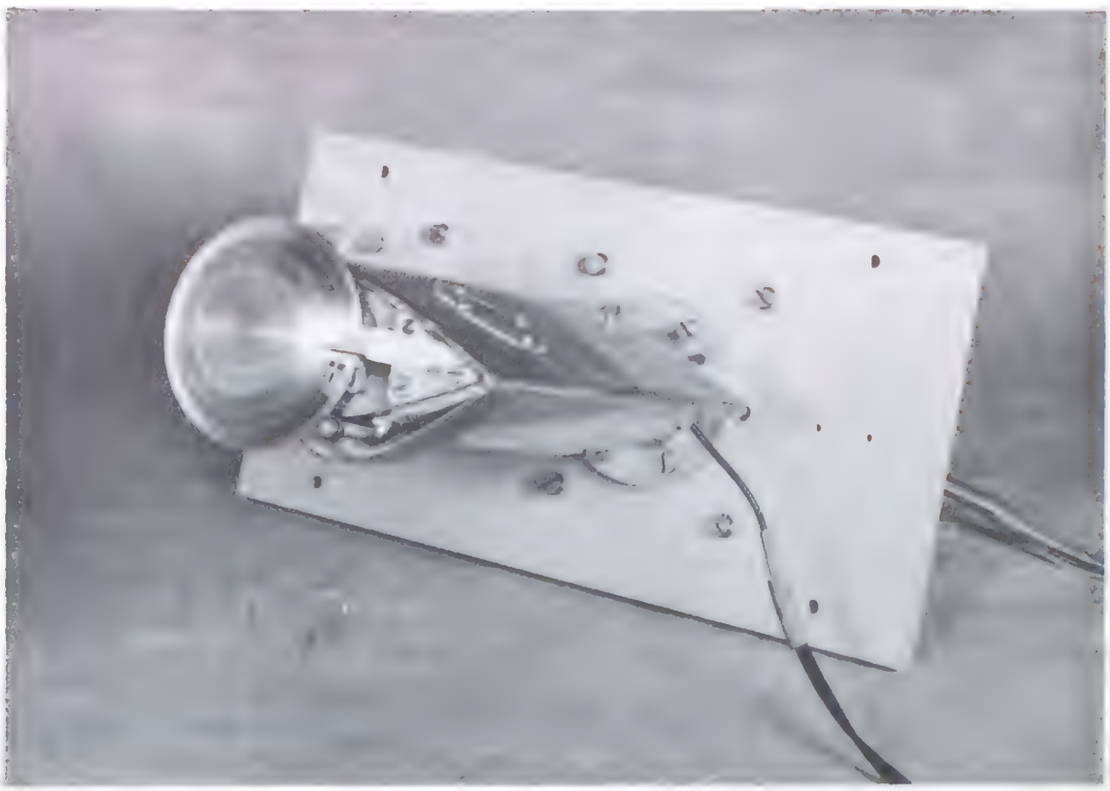


Fig. 2c. Refrigerated Rotating Disc Icing Meter - Top View.

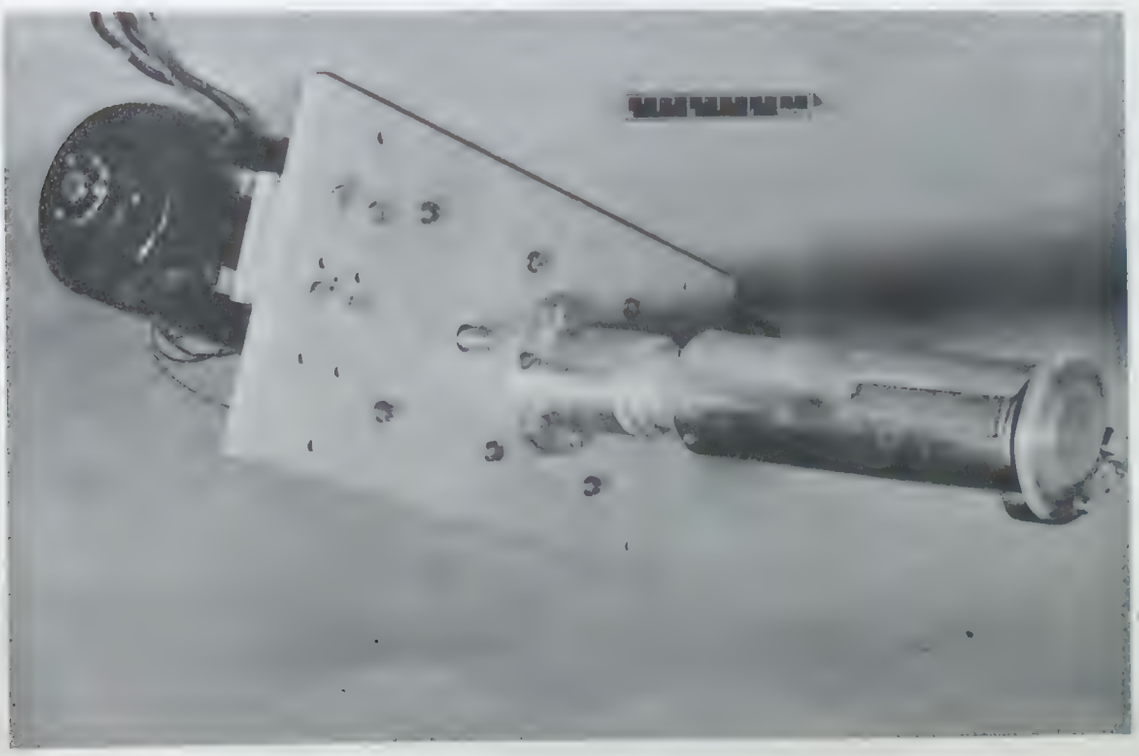
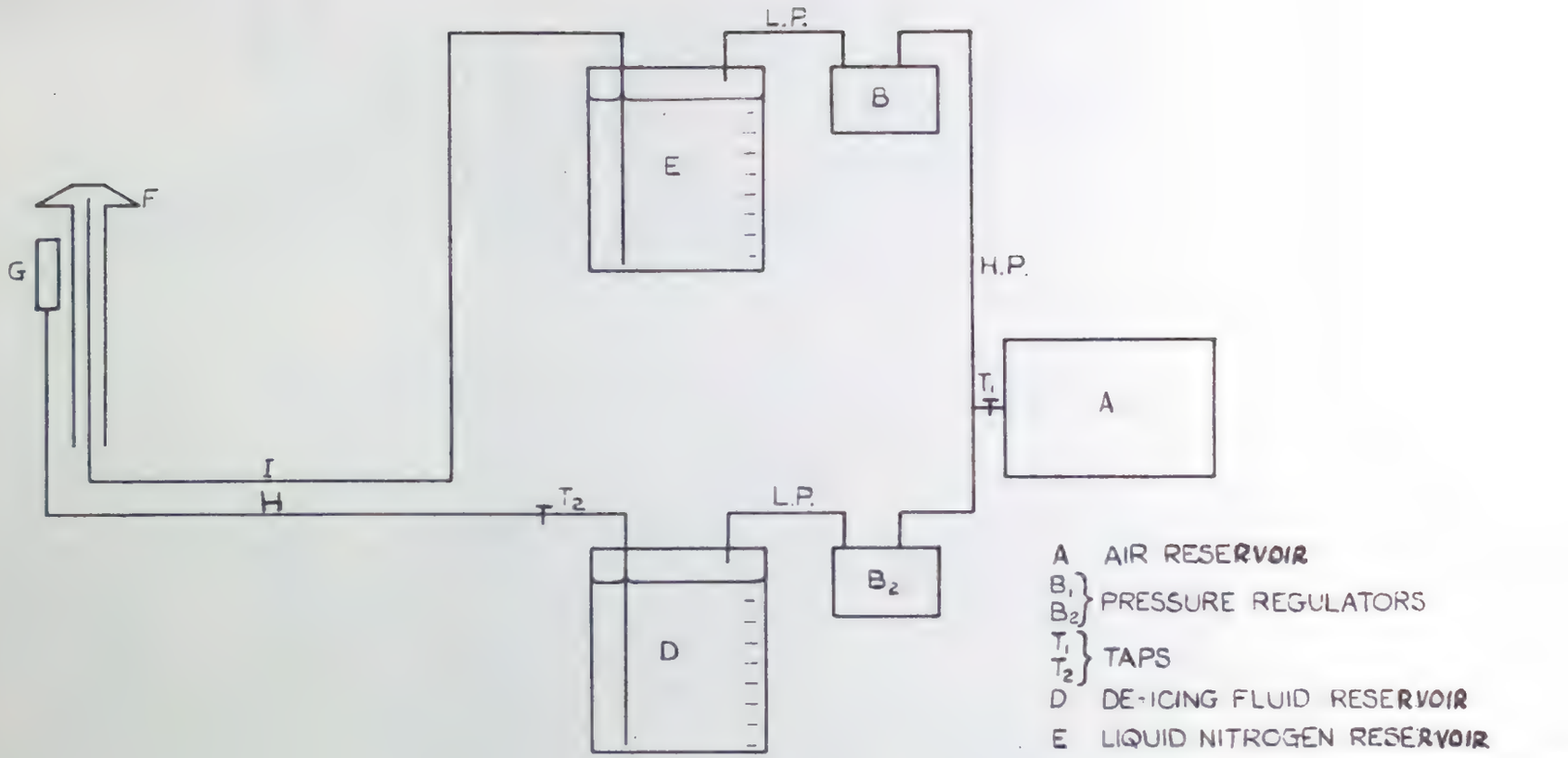


Fig. 2d. Refrigerated Rotating Disc Icing Meter - Front View



A AIR RESERVOIR
B_1, B_2 PRESSURE REGULATORS
T_1, T_2 TAPS
D DE-ICING FLUID RESERVOIR
E LIQUID NITROGEN RESERVOIR
F ROTATING DISC AND HOLLOW SHAFT
G DE-ICING STRIP
H.P. HIGH PRESSURE AIR
L.P LOW PRESSURE AIR
H DE - ICING FLUID
I LIQUID NITROGEN

FIG. 3. FLUID CIRCUITS - SCHEMATIC.

M.R.P. 916
FIG. 3.

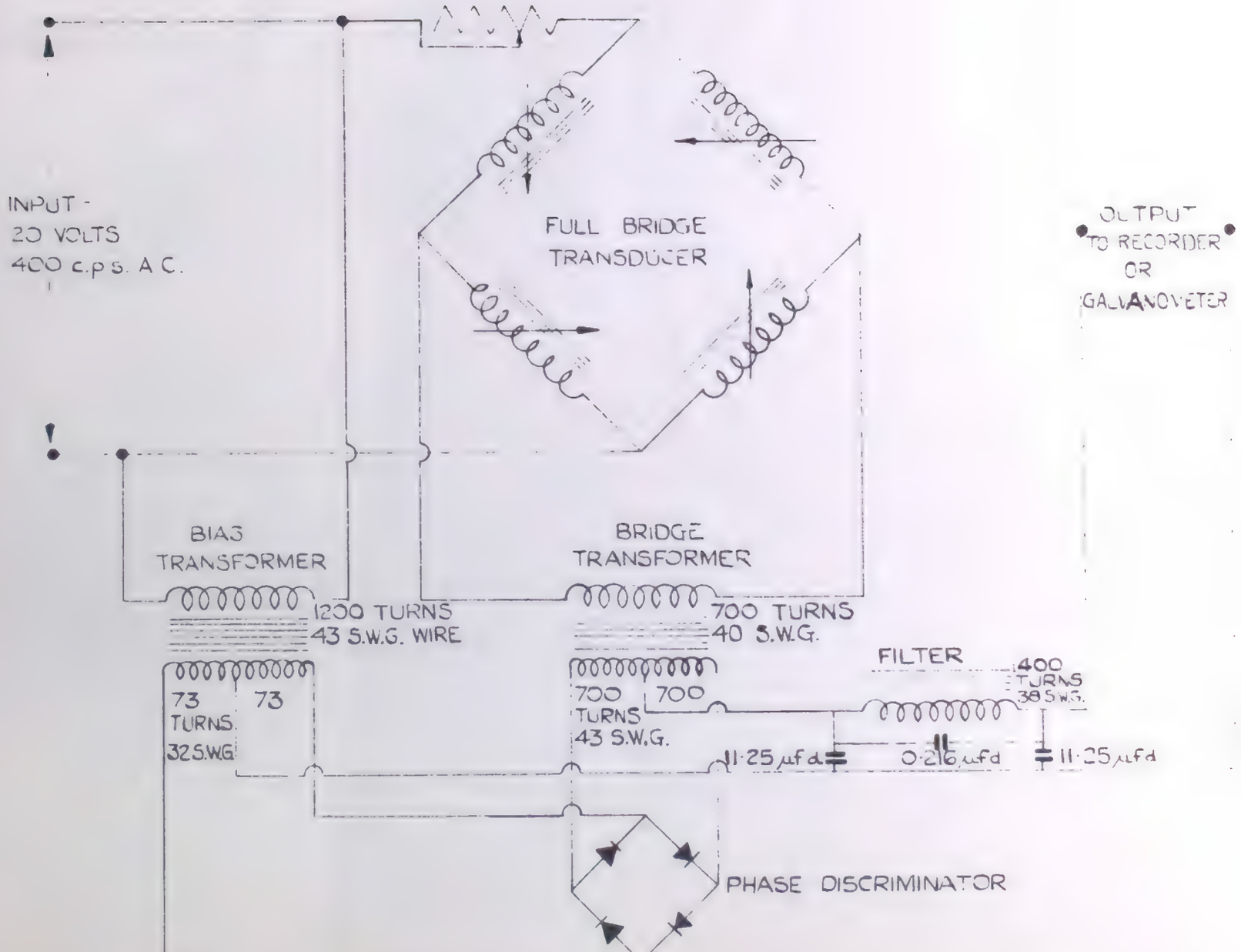


FIG. 4. ICE THICKNESS MEASUREMENT CIRCUIT

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FIG. 4.

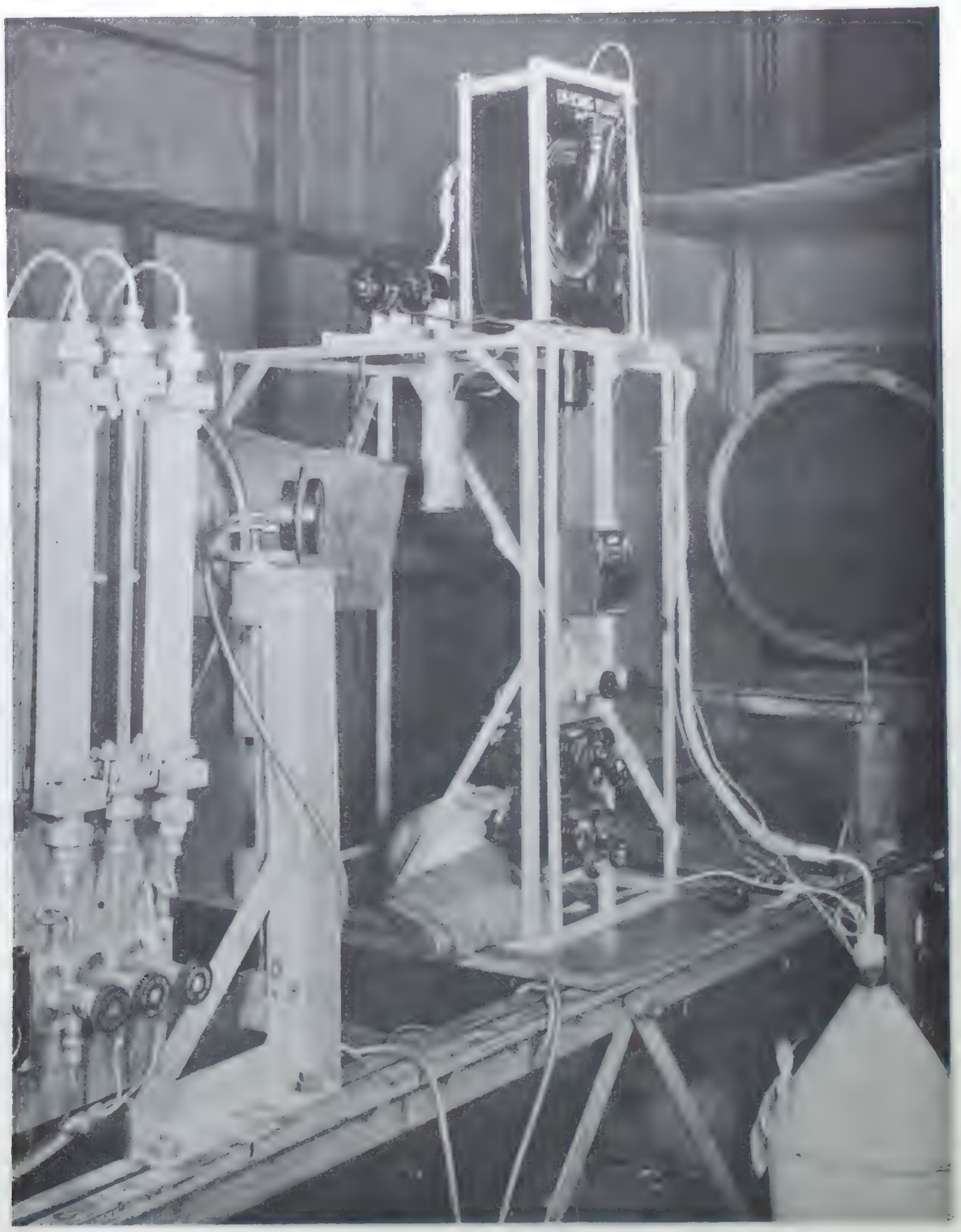

Fig. 5 Instrument under test in Icing Wind Tunnel.

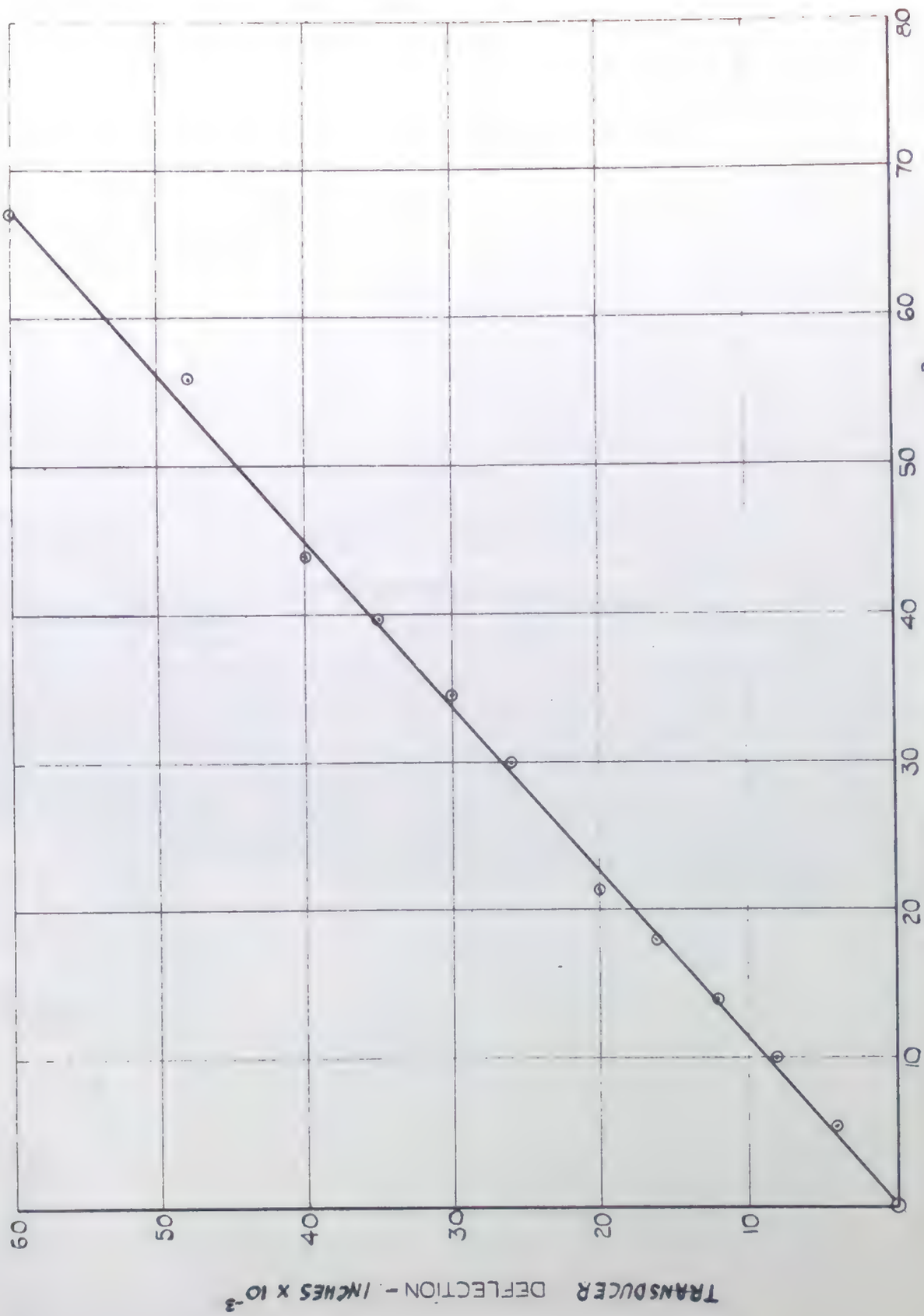

FIG. 6(a). TRANSDUCER PERFORMANCE.

M.R.P. 916

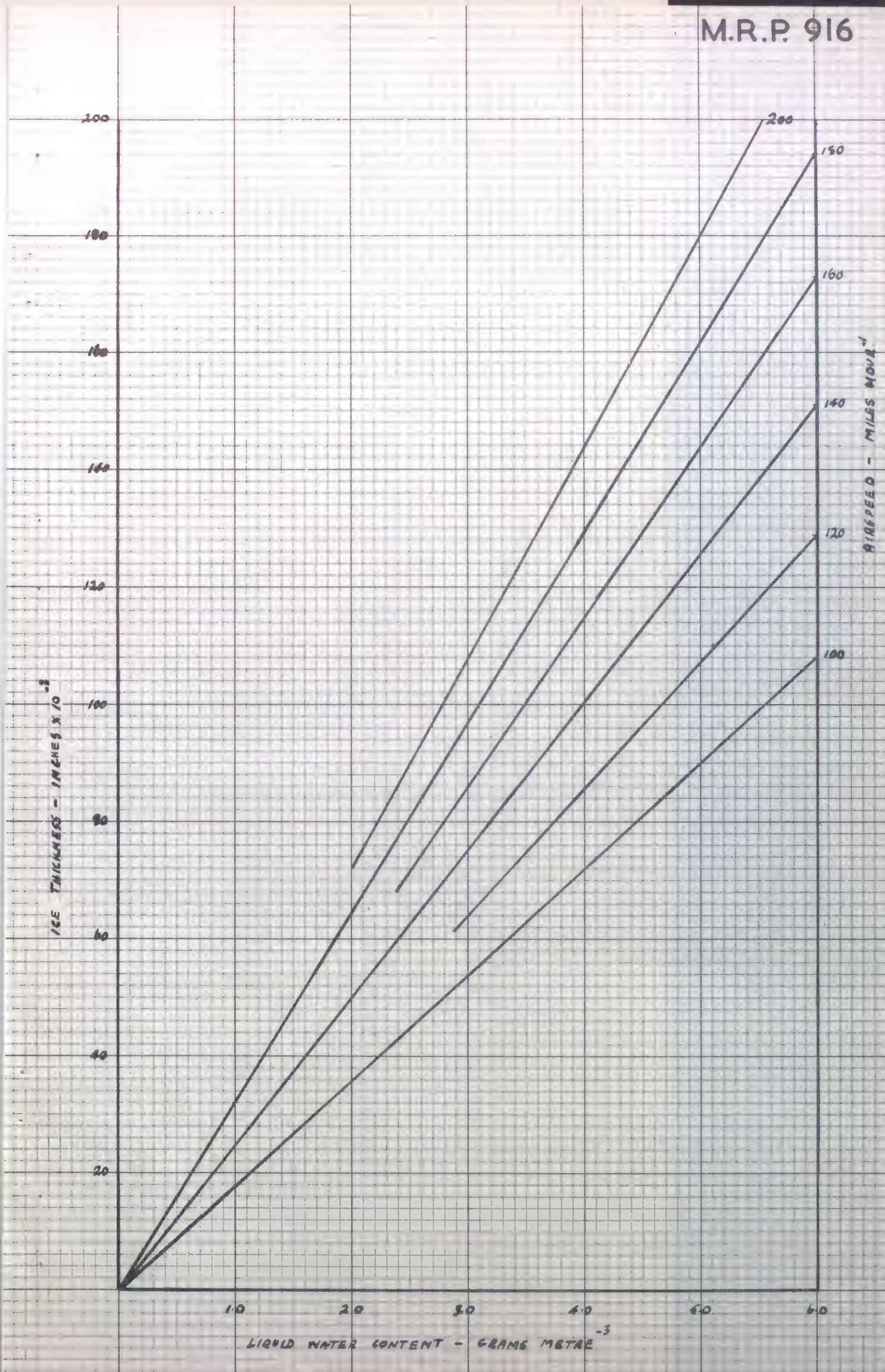

FIG. 6 b. THEORETICAL CALIBRATION BASED ON EQUATION $y = \frac{60 m v E}{\pi n l i}$

M.R.P. 916

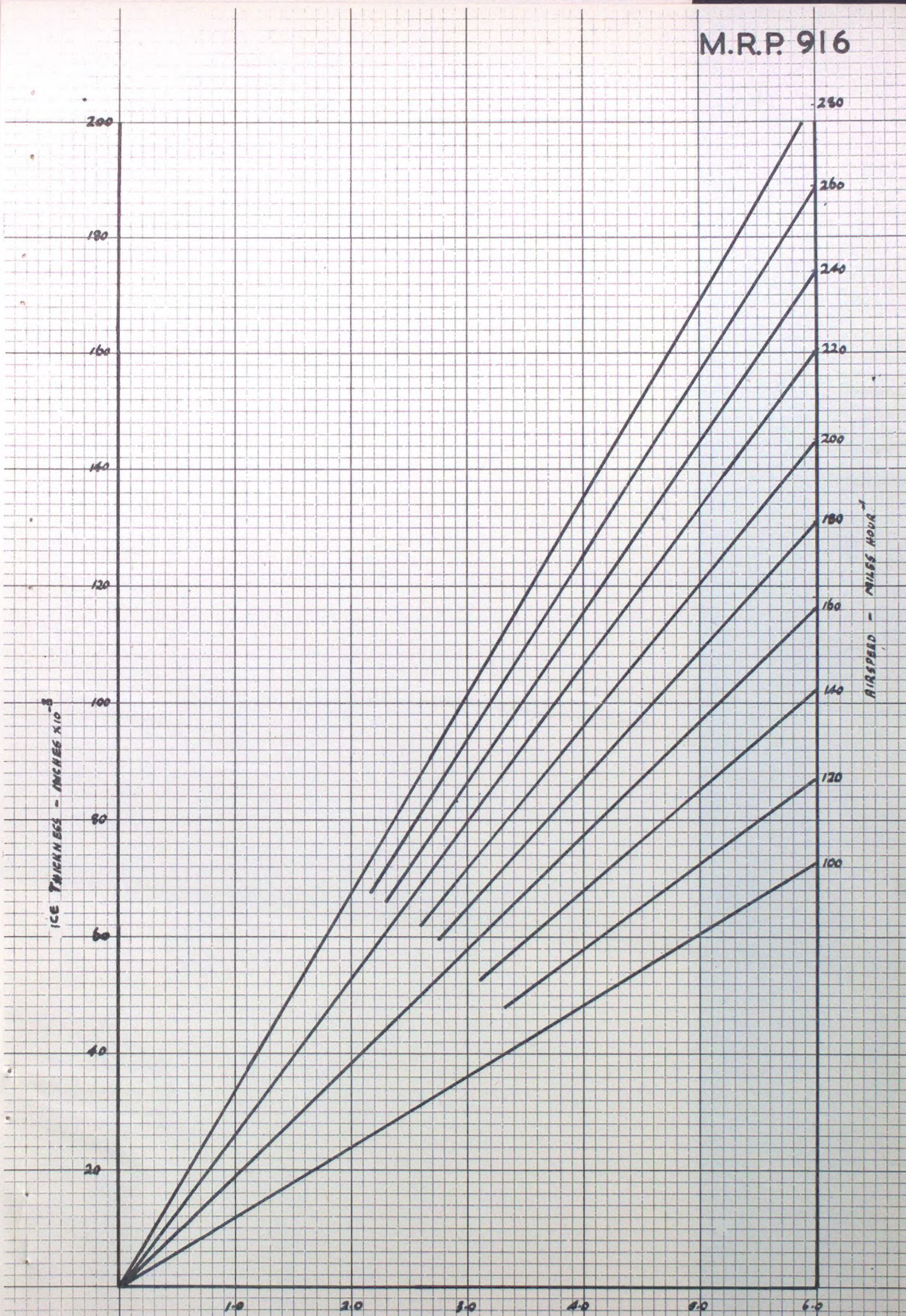

FIG. 6 c. PROVISIONAL EMPIRICAL CALIBRATION OBTAINED IN R.A.E. ICING WIND TUNNEL

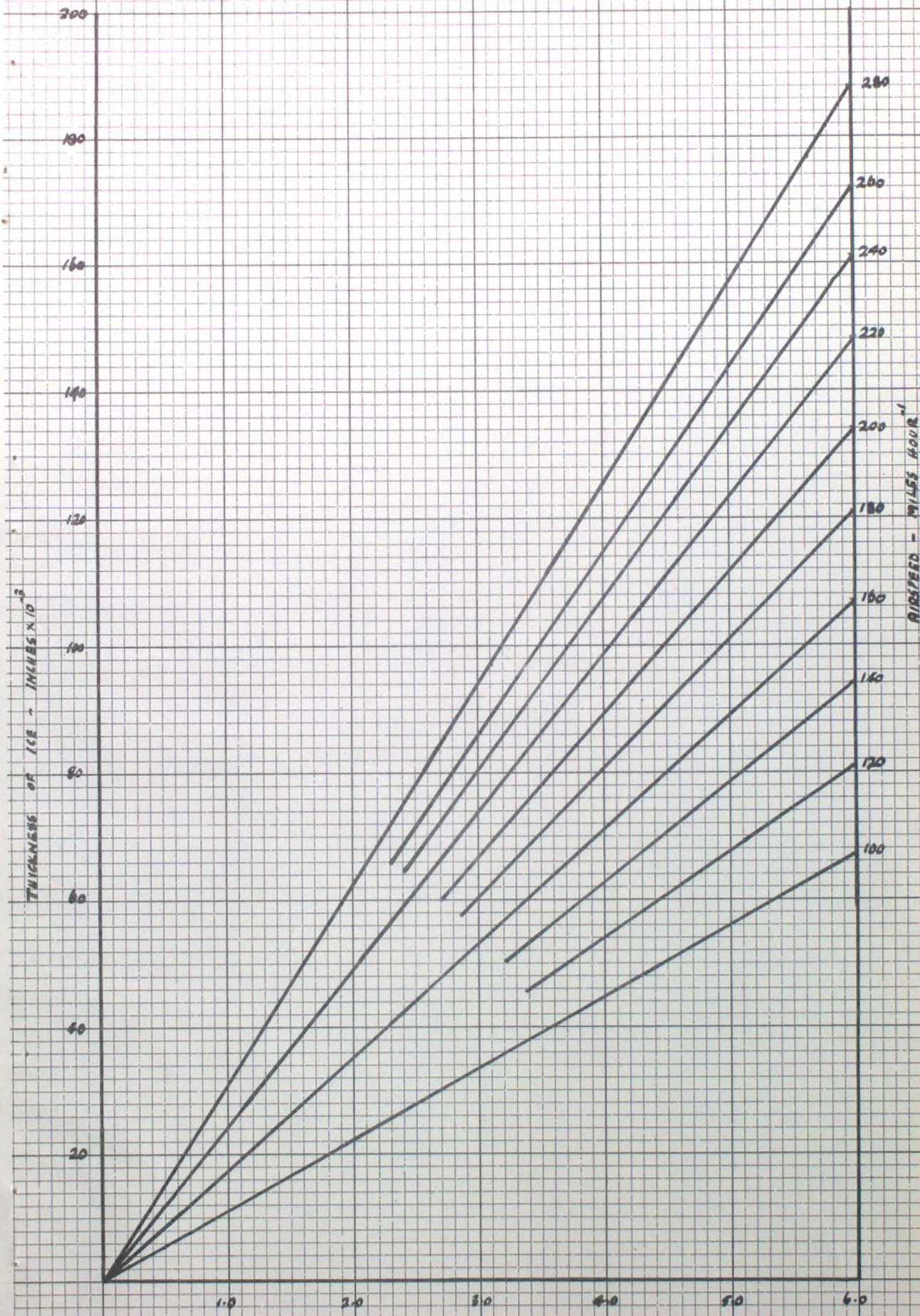

FIG. 6 d. FINAL EMPIRICAL CALIBRATION OBTAINED IN CALIBRATED ICING WIND TUNNEL AT ARTINGTON.

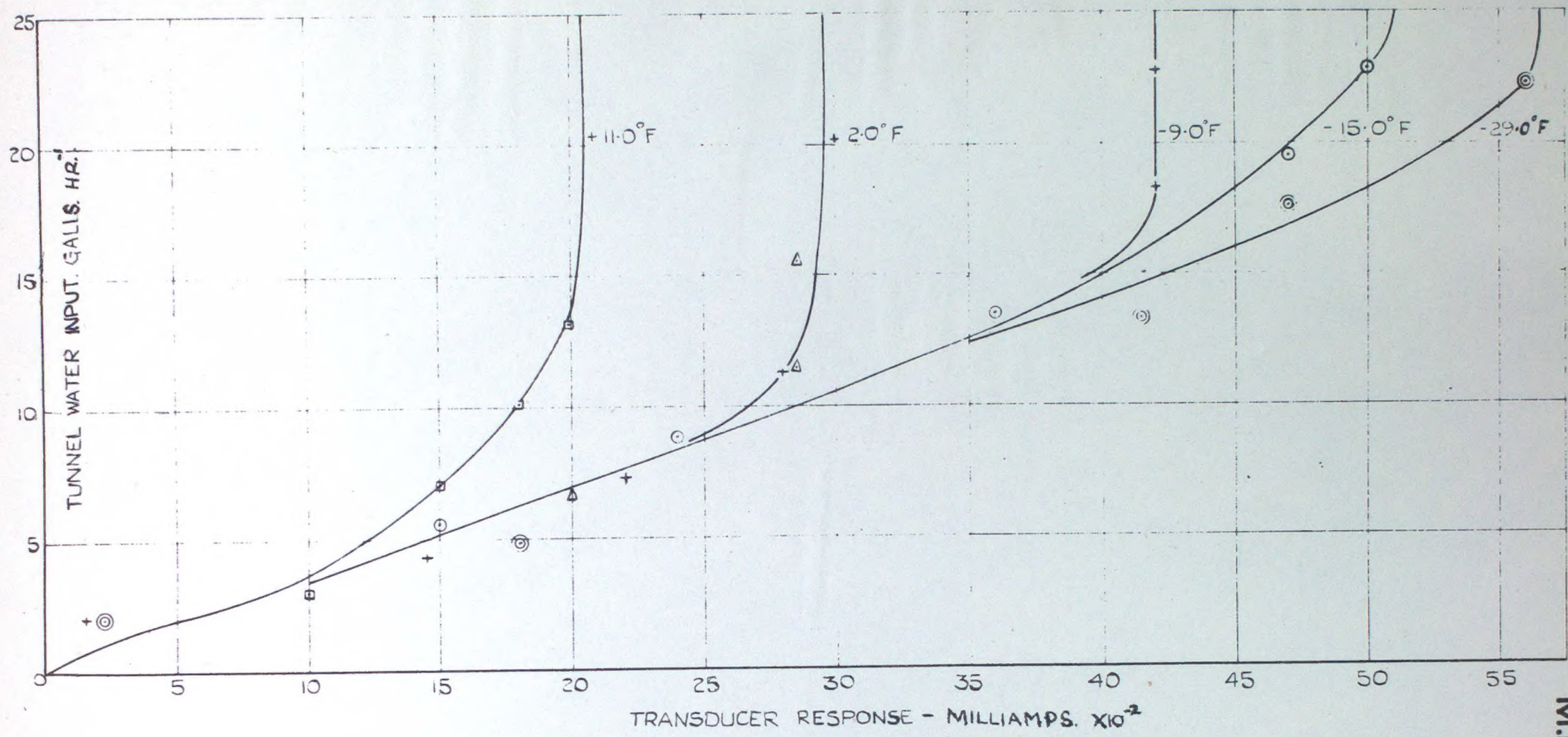

FIG. 7. TRANSDUCER CHARACTERISTICS AT VARIOUS DEGREES OF REFRIGERATION, FIGURES INDICATE DISC TEMPERATURE AT ZERO WATER CONTENT.

M.R.P. 916
FIG. 7.

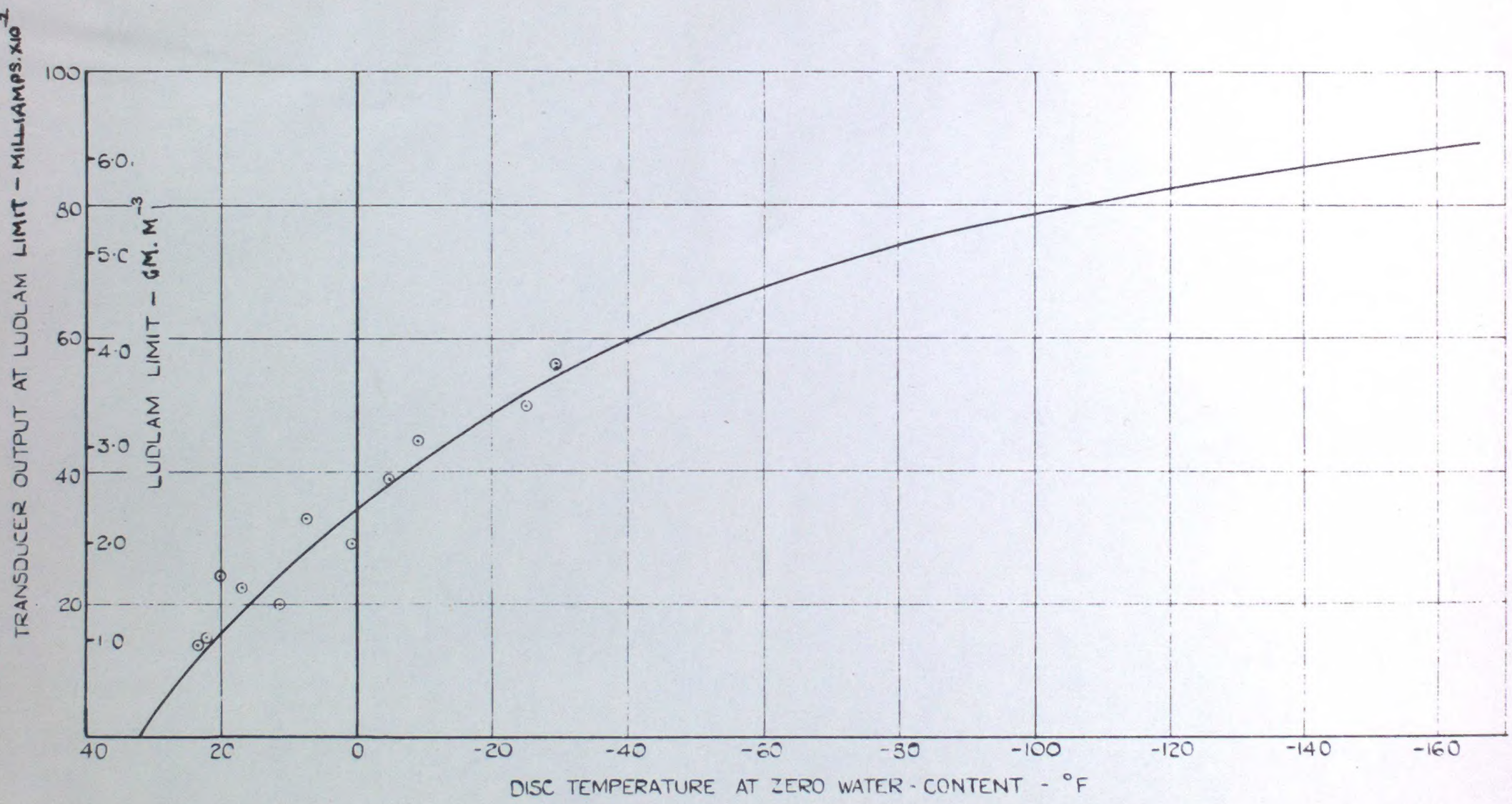

FIG. 8. VARIATION OF LUDLAM LIMIT WITH DEGREE OF REFRIGERATION OF DISC.

M.R.P. 916
FIG. 8.